Chapter Six Types of Vegetative Biofilters and Their Ability to Remove Pollutants

6.1 Introduction

Historically vegetative biofilters, such as grass swales, were used primarily for stormwater conveyance (Ree, 1949; Chow, 1959; Temple, 1987). However with the passage of the Clean Water Act, and the focus on water quality management of urban runoff, the potential for the application of these techniques has begun to be reconsidered and many additional benefits have been identified. Today biofilters are being applied to address design objectives of urban stormwater management. These include: reduction of urban runoff impacts, groundwater recharge, water quality control, stream channel protection, and peak discharge control for both small storms (6-month and 1-year frequency storms), and large storms (2, 10 and 100-year storms). The most common application of the biofilters, however, is typically their use as the first stage of the treatment train approach and their purpose is to partially address groundwater recharge and water quality control for small headwater areas.

Three different types of vegetative biofilter BMP types have been identified and are described in this document. These are: grass swales, vegetated filter strips, and bioretention cells. Grass swales include three variations: traditional grass swales, grass swales with media filters and wet swales.

6.2 Grass Swale

Grass swales have traditionally been used as a low cost stormwater conveyance practice in low-to-medium density residential developments (e.g., ½- acre lots). Most public works agencies throughout the U.S. have a typical rural road sectional that allows the use of vegetated swales within the public right of way. During the early years of stormwater management technology the focus was on peak discharge control and grass swales were not given much consideration. As the focus of stormwater management programs expanded to include water quality considerations and pollutant reduction, the grassed swale has been perceived to represent

a potentially important element of the treatment train approach to total stormwater management (Yousef, et al, 1986; Yu, 1992; Yu, 1993).

Grass swales have a number of desirable attributes with respect to total stormwater management (MDE, 2000; ASCE, 1998; CRC, 1996; Yu, 1993;) including:

- slower flow velocities than pipe systems that result in longer times of concentration and corresponding reduction of peak discharges;
- ability to disconnect directly connected impervious surfaces, such as driveways and roadways thus reducing discharge;
- filtering of pollutants by grass media;
- infiltration of runoff into the soil profile thus reducing discharges, providing additional pollutant removal, and increasing groundwater recharge; and
- uptake of pollutants by plant roots (phytoremediation)

A typical grass swale is shown in Figure 6-1. The section shows that the water quality volume (WQv) is a fraction of the typical 2 and 10 year design storms.

Grass Swale with Media Filters Also known as a dry swale, this grass swale consists of an open channel that has been modified to enhance its water quality treatment capability by adding a filtering medium consisting of a soil bed with an underdrain system (CRC, 1996). It is designed to temporarily store the design water quality volume (WQv) and allow it to percolate through the treatment medium. The system is designed to drain down between storm events within approximately one day. The water quality treatment mechanisms are similar to bioretention cells except that the pollutant uptake is likely to be more limited since only a grass cover crop is available for nutrient uptake.

Wet Swale The wet swale also consists of a broad open channel capable of temporarily routing and storing the water quality volume (WQv) but does not have an underlying filtering bed (CRC, 1996). It is constructed directly within existing soils and may intercept the water table. Like the dry swale, the WQv within the wet swale should be stored for approximately 24 hours. The wet swale has water quality treatment mechanisms similar to stormwater wetlands, both of which rely primarily on settling of suspended solids, adsorption, and uptake of pollutants by vegetative root systems. Figure 6-2 illustrates the design components of the wet swale (MDE, 2000).

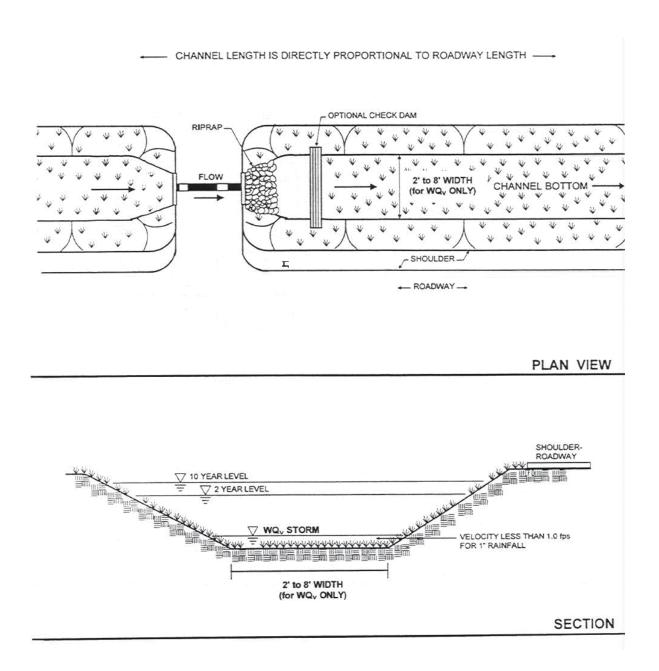
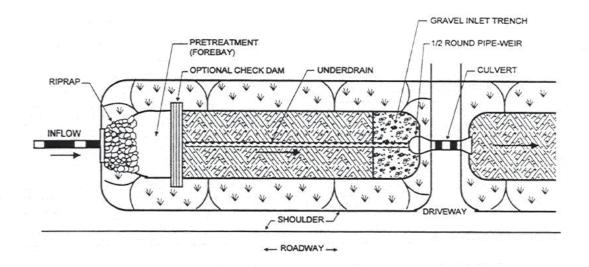


Figure 6-1 Grass Swale (MDE, 2000)



PLAN VIEW

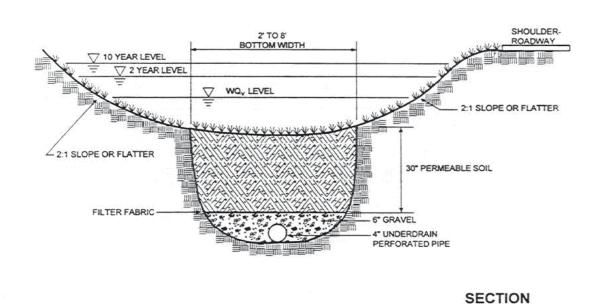


Figure 6-2 Wet Swale (MDE 2000)

6.3 Vegetative Filter Strip

Vegetative filter strips (VFSs) and buffers are areas of land with vegetative cover that are designed to accept runoff as overland sheet flow from upstream development. They can either be constructed or existing. Dense vegetative cover facilitates sediment attenuation and pollutant removal for the design storms. Unlike grass swales, vegetated filter strips are primarily designed for overland sheet flow. Grading and level spreaders can be used to create a uniformly sloping area that distributes the runoff evenly across the filter strip. For small storms that do not discharge, infiltration becomes the primary removal mechanism.

Filter strips have been used to treat runoff from roads and highways, roof downspouts, very small parking lots, and pervious surfaces. They can also be used as the "outer zone" of a stream buffer but are usually most effective as pretreatment to another treatment BMPs such as infiltration basins or trenches. Figure 6-3 illustrates the primary design components of the filter strip (CRC, 1996).

6.4 Bioretention Cell

The bioretention concept was originally developed in the early 1990's as an alternative to traditional BMP structures (Clar, *et al.*, 1993, 1994). Bioretention is a practice to manage and treat stormwater runoff using a conditioned planting soil bed and planting materials to filter runoff stored within a shallow depression. The method combines physical filtering and adsorption with biological processes and usually takes place in a bioretention cell. The system consists of a flow regulation structure, a pretreatment filter strip or grass channel, a sand bed, a pea gravel overflow curtain drain, a shallow ponding area, a surface organic layer of mulch, a planting soil bed, plant material, a gravel underdrain system, and an overflow system. Figure 6-4 illustrates these primary design components of the bioretention cell (MDE, 2000).

6.5 Role in Water Quality Improvement

Table 6-1 summarizes the pollutant removal capability reported as percent removal of biofilter BMPs for the following constituents: TSS, total phosphorus (TP), total nitrogen (TN), Nitrates, (NO3), and metals. Biofilters have some similarities with respect to performance, but their flow reduction and pollution removal capabilities are basically a function of their size relative to the inflow drainage volume (or long-term infiltration capacity volume) ratio (volume/area). For example, all of these facilities typically report relatively high removal rates of suspended sediment, ranging from 68% for the grass channel to 90% or more for the dry swale and the bioretention cell. The bioretention cell is typically much smaller than the other units; therefore, the total loading would be smaller.

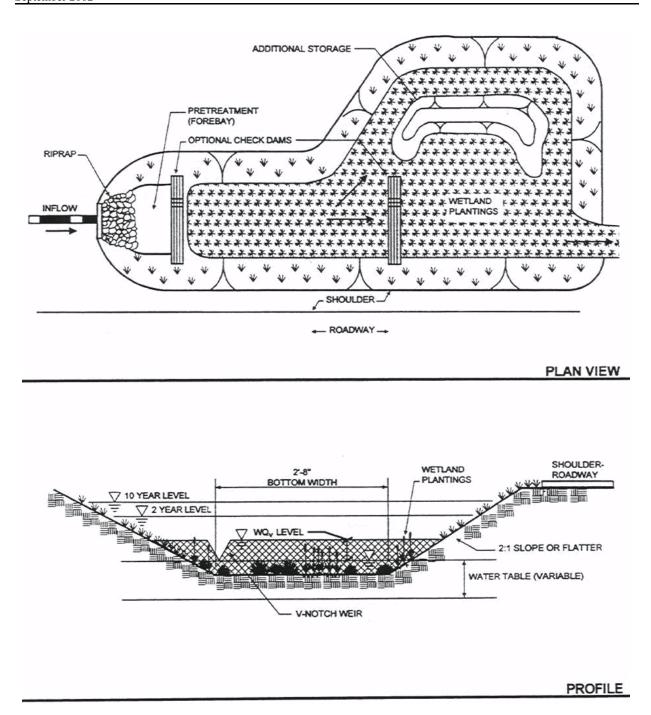


Figure 6-3 Typical Vegetative Filter Strip (CRC, 1996)

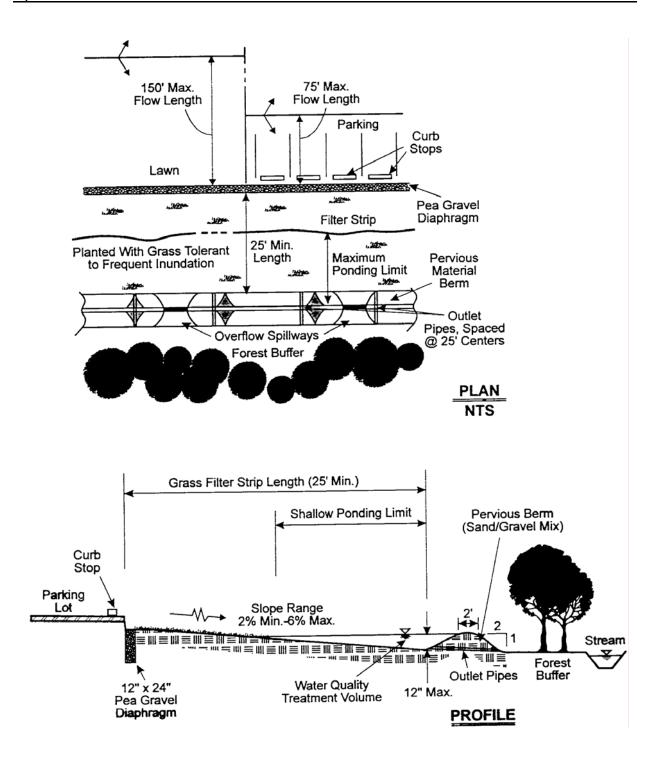


Figure 6-4 Typical Bioretention Cell (MDE, 2000)

Table 6-1 Estimated Pollutant Removal Capability of Biofilters (Winer, 2000; Yu and Kaighn, 1992, Davis et al., 1998)

Biofilter	TSS*	TP	TN	NO ₃	Other / Comments
Grass Swale	68	29	N/A	-25	Metals: Cu (42); Zn (45) Hydrocarbons: 65% Bacteria: Negative
Dry Swale	93	83	92	90	Metals: Cu (70); Zn (86)
Wet Swale	74	28	40	31	Metals: Cu (11); Zn (33)
Filter Strip	70	25	NA	10	Metals: 40-50%
Bioretention	95	83	43	23	Metals: 93-99%

^{*} Removals shown as percentages

Some differences have been observed in the comparative ability to remove total phosphorus. The best performers were the dry swale and bioretention cells with removal rates of 83% and 70% respectively. Grass channels, wet swales and filter strips were less reliable, at 10 to 29% average removal. Vegetative biofilters display a wide range of total nitrogen removal. The dry swale exhibited a very high removal rate of 92%.

While all biofilter designs showed at least moderate capacity to remove trace metals such as copper, lead, and zinc, most of the removed metals were already attached to particles. Designs that showed promise in removing dissolved metals include the dry swale and bioretention cell.

Pollutant removal and mechanisms rely on processes in a generally aerobic environment, as opposed to anaerobic environment. Filters which go anaerobic tend to release previously captured phosphorous as iron phosphates break down.

Compatibility with Land Use Type As a group, vegetative biofilters can be applied to a diverse range of land use types. However, individual designs are limited to a much narrower range. These common land use situations include ultra-urban sites, parking lots, road and streets, small residential subdivisions and backyard/rooftop drainage. Table 6-2 is a matrix that illustrates the most economical and feasible biofilter designs for each of these five broad categories of development, as well as those that are not applicable. As previously discussed, devices that rely on infiltration should take into consideration the fate of possible pollutants in the groundwater.

Table 6-2 Land Use and Biofilter Suitability

Urban Retrofit	Bioretention cell has proven very versatile for use in retrofit conditions. Swales are usually not well suited.			
Parking Lots	Bioretention cell is well suited for use in parking lots. Swales may be suitable under certain conditions (space, soils, water table). Filter strips can be effective (Figure 6-1)			
Roads & Highways	City streets generally do not provide enough space for any biofilter Suburban areas, specially large to medium lot subdivision can accommodate all of the biofilters. Highways may accommodate biofilters if sufficient space is available in median or side slopes.			
Residential	Low density residential affords opportunities for all biofilter uses. High density residential may offer limited opportunity based on space availability.			
Rooftops	Roof drain disconnections to filter strips or bioretention areas are recommended where feasible.			

For example, in ultra-urban or retrofit settings where space is at a premium, the bioretention cell is one of the most versatile biofilters. In most cases, the space requirements of swales and filter strips are so great that they can be eliminated from consideration in downtown urban areas, but bioretention cells may be considered as a retrofit to partially treat urban runoff.

Compatibility with Site Conditions Table 6-3 compares how each biofilter design compares with respect to a number of site conditions, including soils, water table, drainage area, slope head and space consumed.

6.6 Design of Grass Swales for Pollutant Removal

Pollutants are removed in swales by settling, deposition in low velocity areas, or by infiltration into the subsoil. The primary pollutant removal mechanism is through sedimentation of suspended materials for larger particles and infiltration for colloidal particles and dissolved solids. Therefore, suspended solids and adsorbed metals are most effectively removed through the traditional grass swale (rather than the swale with filter media or wet swale). Removal efficiencies reported in the literature vary, but generally fall into the low-to-medium range, with some swale systems recording no water quality effects at all. Schueler (1992), reported that of 10 swales monitored, 50 percent registered moderate pollutant removal, while the remainder showed negligible or negative removal.

The amount of pollutant removed will depend on the length of the swale. Table 6-4 presents the pollutant removal efficiencies for 200 ft and 100 ft swale lengths. Although research results varied, these data clearly indicate increased pollutant removal efficiencies with longer swales.

Table 6-3 Physical Site Conditions and Biofilter Suitability (modified from MDE, 2000)

Biofilter	Soils	Water Table (depth)	Drainage Area (acres)	Slope Limits	Head	Area Required
1) Grass Swale	ОК	2 feet	5 max	6% max.	2 feet	6.5%
Dry Swale	Filter Media	2 feet	5 max	6% max	3 to 6 feet	10-20%
Wet Swale	ОК	Below WT	5 max	6% max	1 foot	10-20%
2) Filter strip	OK	2 feet	N/A	15% max	N/A	100%
3) Bioretention Cell	Filter Media	2 feet	2 max	None	5 feet	5.0%

Notes: Soils - the key evaluation factors are based on an initial investigation of the USDA HSG at the site. More detailed geotechnical tests are usually required for infiltration feasibility and during design to confirm permeability and other factors

Water table - the minimum depth to the seasonally high water table from the bottom or floor of a BMP.

Drainage Area - the recommended minimum or maximum drainage area that is considered suitable for the practice. If

the drainage area present at a site is slightly greater than the maximum allowable drainage area for a practice, some leeway is permitted or more than one practice can be installed.

Slope Restriction - the effect of slope on the practice. Specifically, the slope restrictions refer to how flat the area where the practice may be.

Head - an estimate of the elevation difference needed at a site (from the inflow to the outflow) to allow for gravity operation within the practice.

Area Required - indicates percentage of total drainage area requirement for BMP.

Table 6-4 Pollutant removal efficiencies for grass swales (Barret, et al., 1993; Schueler, 1991; Yu,1993; Yousef, et al., 1985; Horner, 1996)

	Pollutant Removal Efficiencies (%)								
Design	Solids	Nutrients		Metals			Other		
	TSS	TN	TP	Zn	Pb	Cu	Oil & Grease	COD**	
200-ft grass swale	83	25*	29	63	67	46	75	25	
100-ft grass swale	60	0	45	16	15	2	49	25	

^{*}Some swales, particularly 100-ft systems, showed negligible or negative removal for TN.

^{**}Data is very limited.

In general, the current literature reports that a well-designed, well-maintained swale system can be expected to remove 70% of total suspended solids (TSS), 30 percent for total phosphorus (TP), 25 percent for total nitrogen (TN), and 50 to 90% for trace metals (Barret, et al., 1993; GKY, 1991). The TN removals may be fairly optimistic, given that studies conducted by Yousef et al. (1985) and others produced negative nitrogen removal in many cases, possibly due to the remobilization of nitrogen from grass clippings and other organic materials.

Seasonal differences in swale performance can be important. In temperate climates, fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of runoff pollutants, and removing an important mechanism for flow reduction. Decomposition in the fall, and the absence of grass cover in the winter can often produce an remobilization of nutrients, and may expose the swale to erosion during high flows, increasing sediment loads downstream. Pollutant removal efficiencies for many constituents can be markedly different during the growing and dormant periods (Driscoll and Mangarella, 1990).

6.7 Design of Vegetative Filter Strips for Pollutant Removal

Pollutants are removed in filter strips mainly by settling for larger particles and by soil infiltration for colloidal particles. Under low-to-moderate velocity, filter strips effectively reduce particulate pollutant levels by removing sediments and organic materials and trace metals (Schueler, 1992). Research has shown removal of 70% for TSS, 40% to 50% for phosphorus (particulate) and zinc, 25% for lead, and 10% for nitrate/nitrite (Florida Department of Transportation, 1994). Settling of aggregate containing clay particles removes sorbed nutrients and other pollutants. Removal of free soluble pollutants in filter strips is accomplished when pollutants infiltrate into the soil, some of which are subsequently taken up by rooted vegetation. Therefore, removal of solubles depends on the infiltration rates. The mechanism for infiltration is minor in most filter strips during design storms or larger storms since only a modest portion of the incoming runoff is infiltrated and most discharges, resulting in low removal rates for solubles, but is the dominant mechanism for small storms that totally infiltrate.

Pollutant removal in filter strips is a function of length, slope, soil permeability, size of contributing runoff area and its long-term contributing inflow volume, particle size and settling velocity, and runoff velocity (Schueler, 1987 and Hayes et al., 1984). A wide range of values for minimum length in the flow direction have been reported in the literature. Frequently cited values range from 20 ft to lengths of 100 to 300 ft for adequate removal of the smaller particles. The design guidance that follows provides analytical procedures for computing these values.

Regardless of vegetation type, the length of the filter strip is shown to have significant influence on pollutant removal. Figure 6-5 provides one example of percent pollutant removal efficiency versus length (Yu and Kaighn, 1992). In Figure 6-5, the relative value of adding additional length to a filter strip for pollutant removal levels off significantly after 59 ft, with the most significant rise in removal occurring between 19 to 59 ft. However, strip length alone does

not entirely define pollutant removal. The existing longitudinal slope and soil infiltration capacity will also influence the ultimate length of the system. These factors may dictate a strip longer than would be necessary if pollutant removal alone was the only consideration.

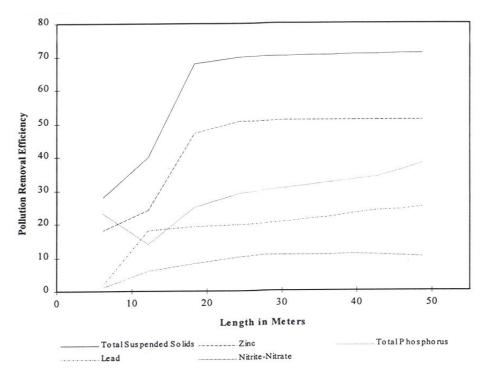


Figure 6-5 Pollutant Removal Efficiency Versus Filter Strip Length (Yu and Kaighn, 1992)

In design, the variables that can be effectively manipulated include length and slope of the strip, soil characteristics and vegetative cover. According to Yu and Kaighn (1992), optimum lengths were between 20 to 30 m for a given sheetflow over the filter strip and inflow to outflow pollutant removals. Higher pollutant removal rates for longer lengths were feasible; however, further improvements in pollutant removal are relatively minor. The design length would be expected to vary widely with slope, settleable particle size, soil type, infiltration capacity and vegetation type. Avoiding the potential for concentrated flows and "gullies" will effectively "short-circuit" the filter strip and significantly reduce removal rates. Width can also influence pollutant removal but is often constrained by the area available.

VFS Enhancements - Level Spreader A level spreader should be provided at the upper edge of a vegetated filter strip when the width of the contributing drainage area is greater than that of the filter. Runoff may be directed to the level spreader as sheet flow or concentrated flow. However, the design must ensure that runoff fills the spreader evenly and flows over the level lip

as uniformly as possible. The level spreader should extend across the width of the filter, leaving only 10 feet open on each end.

There are many alternative spreader devices, with the main consideration being that the overland flow spreader be distributed equally across the strip. Level spreader options include porous pavement strips, stabilized turf strips, slotted curbing, rock-filled trenches, concrete sills, or plastic-lined trenches that act as a small detention pond (Yu and Kaighn, 1992). The outflow and filter side lip of the spreader should have a zero slope to ensure even runoff distribution (Yu and Kaighn, 1992). Once in the filter strip, most runoff from high storm flow events will not be infiltrated and will require a collection and conveyance system. Grass-lined swales are often used for this purpose and can provide another BMP level. A filter strip can also drain to a storm sewer or street gutter (Urbonas, 1992).

VFS Enhancements - Pervious Berm A pervious berm may be installed at the foot of the strip to force ponding in a VFS. It should be constructed using a moderately permeable soil such as ASTM ML, SM, or SC. Soils meeting USDA sandy loam or loamy sand texture, with a minimum of 10 to 25% clay, may also be used. Additional loam should be used on the berm (\pm 25%) to help support vegetation. An armored overflow should be provided to allow larger storms to pass without overtopping the berm. Maximum ponding depth behind a pervious berm should be 1 foot.

VFS Enhancements - Types of Vegetation to Use A VFS should be densely vegetated with a mix of erosion resistant plant species that effectively bind the soil. Certain plant types are more suitable than others for urban stormwater control. The selection of plants should be based on their compatibility with climate conditions, soils, and topography and the their ability to tolerate urban stresses from pollutants, variable soil moisture conditions and ponding fluctuations.

A filter strip should have at least two of the following vegetation types: deep-rooted grasses and ground covers; or deciduous and evergreen shrubs; or under- and over-story trees. Native plant species should always be specified. This will facilitate establishment and long term survival. Non-native plants may require more care to adapt to local hydrology, climate, exposure, soil and other conditions. Also, some non-native plants may become invasive, ultimately choking out the native plant population. This is especially true for non-native plants used for stabilization.

Newly constructed stormwater BMPs will be fully exposed for several years before the buffer vegetation becomes adequately established. Therefore, plants which require full shade, are susceptible to winter kill or are prone to wind damage should be avoided. Plant materials should conform to the American Standard for Nursery Stock, current issue, as published by the American Association of Nurserymen. The botanical (scientific) name of the plant species should be according to the landscape industry standard nomenclature. All plant material specified should be suited for USDA Plant Hardiness Zones.

Grassed filter strips should be constructed of dense, soil-binding deep-rooted water-resistant plants. Dense turf is needed to promote sedimentation and entrapment, and to protect against erosion (Yu and Kaighn, 1992). Turf grass should be maintained to a blade height of 50 to 60 mm (2 to 4 in). Most engineered, sheet-flow systems are seeded with specific grasses. Common grasses established for filter strip systems are rye, fescue, reed canary, and Bermuda (Horner, 1996). Tall fescue and orchard grasses grow well on slopes and under low nutrient conditions (Horner, 1996). The grass species chosen should be appropriate for the climatic conditions and maintenance criteria for each project.

Retaining existing trees and woody vegetation have been shown to increase infiltration and improve performance of filter strips. Trees and shrubs provide many stormwater management benefits by intercepting some rainfall before it reaches the ground, and improving infiltration and retention through the presence of a spongy, organic layer of materials that accumulates underneath the plants (Schueler, 1987). As discussed previously in this section, wooded strips have shown significant increases in pollutant removal over grass strips. Maintenance for wooded strips is lower than grassed strips, another argument for using trees and shrubs. However, there are drawbacks to using woody plants. Since the density of the vegetation is not as great as a turf grass cover, wooded filter strips need additional length to accommodate more vegetation. In addition, shrub and tree trunks can cause uneven distribution of sheet flow, and increase the possibility for development of gullies and channels. Consequently, wooded strips require flatter slopes than a typical grass cover strip to ensure that the presence of heavier plant stems will not facilitate channelization.

Filter strips managed to allow "natural succession" of vegetation from grasses to shrubs and trees provides excellent urban wildlife habitat. Judicious planting of selected native shrub and trees can be used to enhance the quality of food and cover for a variety of animal species (Schueler, 1987). Compaction of soils during construction may not be appropriate for planting of shrubs and trees as growth of a healthy root structure may be inhibited. To facilitate this approach, a landscaping plan should be included in the project specifications.

Construction Guidelines Overall, widely accepted construction standards and specifications, such as those developed by the USDA Natural Resources Conservation Service or the U.S. Army Corps of Engineers, should be followed where applicable to construct a vegetated filter strip. The specifications should also satisfy all requirements of the local government.

Sequence of Construction Vegetated filter strip construction should be coordinated with the overall project construction schedule. Rough grading of the filter strip should not be initiated until adequate erosion controls are in place.

6.8 Design of Bioretention Cells for Pollutant Removal

Since this is a relatively new BMP, the available data on the pollutant removal performance of bioretention cells is scarce. The preliminary reports from field monitoring activities (Table 6-5) are verifying that this BMP not only met local water quality control criteria, but actually ranked as one of the most effective pollutant removal BMPs available. Percent removals will depend on filter media used, influent pollution concentrations, hydraulic loadings and other factors.

Table 6-5 Pollutant Removal Performance of Bioretention Practices (% Removal) (Davis et al, 1997)

	Cu	Pb	Zn	P	TKN	NH ₄	NO ₃	TN
Upper	90	93	87	0	37	54	-97	-29
Zone								
Middle	93	99	98	73	60	86	-194	0
Zone								
Lower	93	99	99	81	68	79	23	43
Zone								

The University of Virginia, Charlottesville, Virginia has initiated a long term study of the performance of a bioretention cell. This study differs from the two bioretention studies conducted in Maryland that monitored a single storm event (3 inches of rainfall). The UVA study is providing performance data based on an annual hydrologic budget. Initial, first year results indicate that the performance of the bioretention cells will exceed all expectations. First year removal results are as follows: 86% for TSS, 90% for TP, 97% for COD and 67% for oil and grease (Yu, et al. 1999).

Unlike the other vegetative biofilters that have a dual function of stormwater transport or detention and pollutant removal, bioretention cells primary function is pollutant removal. For this reason, bioretention cells would perform best as part of a treatment train. Bioretention can also be an effective retrofit BMP for existing urban areas that already have stormwater drainage systems.